END

FILMED

DTIC.

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS

②

AD-A152 172

INVERSION OF RAYLEIGH - WAVE GROUP VELOCITIES FROM HIGH- EXPLOSIVE TESTS

FINAL REPORT
to
U. S. Air Force Office
of Scientific Research

DTIC
ELECTE
APR 4 1985
S   D
B

California State University, Northridge
Department of Geological Sciences
Dr. Gerald W. Simila

TABLE OF CONTENTS

A-1

ABSTRACT

Rayleigh-wave group-velocity data have been obtained by the moving window analysis of high-explosive ground motion records at McCormick Ranch, Kirtland AFB. Fundamental mode velocities (225 to 264 m/s) were determined for the period range 50-160 ms at a recording distance of 229 m. Also, higher mode dispersion was observed for periods 25-60 ms with group velocities of 280-305 m/s. Possible spall phase dispersion was observed at distances of 11-36 m.

Seismic refraction surveys provided initial model parameters for the test site. An iterative inversion method was used to estimate the shear velocity distribution. Constant layer thicknesses and attenuation values equal 50-100 were additional initial constraints. Inversion results yielded a shear-wave velocity model of 245-610 m/s to a depth of 24 m at McCormick Ranch.

I. TECHNICAL DISCUSSION

Introduction

Few investigations have been directed towards the characterization of surface explosions. Recently, Stump and Reinke (1981) and Stump (1981) have calculated synthetic seismograms to model high-explosive tests to understand the effects of energy coupled directly into the ground at the explosive source. They concluded that both the explosive source characterization and the propagation path effects must be suitably resolved to adequately model the ground motion history, especially the "spall" waveform. In order to separate the source and propagation path effects, the geologic structure and P- and S- wave velocities must be determined.

This project involved two specific techniques to process the explosion waveforms and extract information that yielded information regarding the local geologic structure and velocity distribution. The investigation utilized a signal processing technique to determine the dispersive character of the Rayleigh waves generated from high-explosive tests at the McCormick Ranch, New Mexico in 1978-80.

In studying surface waves, one must differentiate between the group and phase velocity of the waveforms. For nondispersive media, the group velocity is equivalent to the phase velocity, and the seismic pulse propagates from the source without a change in shape. In the case of a dispersive media, each component of the wave motion travels with its own characteristic velocity, the phase velocity. In addition, the group velocity is the velocity

associated with a packet of waves of a given frequency (Kovach, 1978).

The group velocity controls the waveform observed on a seismogram. The group velocity (U) is a function of period (T), and is related to the phase velocity (C) by the expression:

$$U = C + k dC/dk$$

$$= - C - \lambda \, dC/d$$

where $k = 2\pi/CT$.

Now, the group velocities of the dispersed waveform can be calculated by the simple equation:

$$U(T) = x/t$$

where x = distance, t = travel time, T = wave period.

This single-station method to determine group velocity is appropriate since explosion data are recorded at varying azimuths and distances.

Various digital processing techniques have been applied to surface waves to determine group-velocity dispersion curves. The specific approach used in this investigation will be the moving-window technique (Landisman and others, 1969) to determine Rayleigh-wave group-velocities. The method is a frequency-time analysis which calculates a two-dimensional array of Fourier amplitudes as a function of wave period. The group-velocity dispersion curve is traced through the Fourier amplitude maximum for each period.

The Haskell method (Haskell, 1953) is used to generate theoretical Rayleigh-wave group-velocity dispersion curves. A linear inversion computer program by Silva (1978) is utilized in a iterative approach for the inversion of the Rayleigh-wave group-velocity data to determine shear-wave velocity structure. The inversion method uses a damped Gauss-Newton algorithm which incorporates the decomposition theorem for an overdetermined system (Lancsoz, 1961). The resolution matrix is also used to evaluate the resolving potential of the model. The partial derivatives of the group velocity are calculated by the method of Rodi and others (1975). The derivatives are numerically calculated using a 5% parameter change. This method has been used successfully by Simila (1980) to determine the crustal shear-wave velocity structure of northern California from the analysis of Rayleigh-wave group-velocities.

Objectives

The specific objectives for this investigation were:

(1) determine the dispersive characteristics of compressional

and Rayleigh waves generated from high-explosive tests by using the moving window technique, and

(2) determine the detailed shear-wave velocity structure of the test site by inversion modeling of the observed group velocities.

Data Set

The data set used in this investigation was provided by the Air Force Weapons Lab (AFWL), Kirtland AFB, New Mexico. The data were supplied on magnetic tape and the data specifications are described in the next section.

II. TECHNICAL ANALYSIS

Introduction

The moving window technique was utilized successfully to extract group-velocity dispersion data from high-explosive ground motion records from the McCormick Ranch (Simila, 1982). The general results involved fundamental Rayleigh-wave group-velocities (225-264 m/sec) that were determined for period range 50-164 msec and distance range 73-229 m. The Haskell method was used to model in a forward manner the dispersion data. The resulting shear-wave velocity distribution for the test site is V_S = 224-400 m/sec for depth range 0-22 m. In addition, possible body wave dispersion was observed for period range 20-40 msec. This investigation presented the first known attempt to evaluate high-explosive ground motion data for Rayleigh-wave group-velocity dispersion using the moving window technique for such a short period range. Previously, a study by Cherry and others (1978) analyzed Rayleigh - wave

dispersion (period = 0.5-4 sec) recorded in alluvial valleys. Recently, Barker and Stevens (1983) determined the shallow shear wave velocity and Q structure in alluvium near El Centro, California. They obtained Rayleigh-wave group velocities equal 120-220 m/s for periods of 40-400 msec. To a total depth of 100 m, the inversion results indicated V_S = 150-450 m/s and Q = 20-120.

Observations

The data used in the investigation were strong-motion seismic records from a series of high-explosive tests in 1978-79 at McCormick Ranch, New Mexico (see Figure 1). The data were recorded by vertical accelerometers (Endevco Model series 2260) and recorded on magnetic tape. Tha analog acceleration recordings were sampled at a rate of 2000 samples per sec with an antialias filter at 400 Hz. The data were recorded at distance ranges of 6.55 to 228.6 m (Stump and Reinke, 1981).

The Pre-Multiple Burst (PMB) high-explosive program was conducted by the AFWL in September, 1978. A series of small bursts, both buried and above ground, with single and multiple-charge configurations were performed (Brown, 1980). Another series of high-explosive tests was conducted in 1979. These tests, Pre-Hybrid Gust (PHG), involved single burst covered and surface tangent bursts along with hexagonal array multibursts equivalents (Babcock, 1980). The data from these experiments were chosen to determine Rayleigh-wave group-velocity dispersion, and to compare the velocity models determined by previous geophysical studies (Stump and Reinke, 1981).
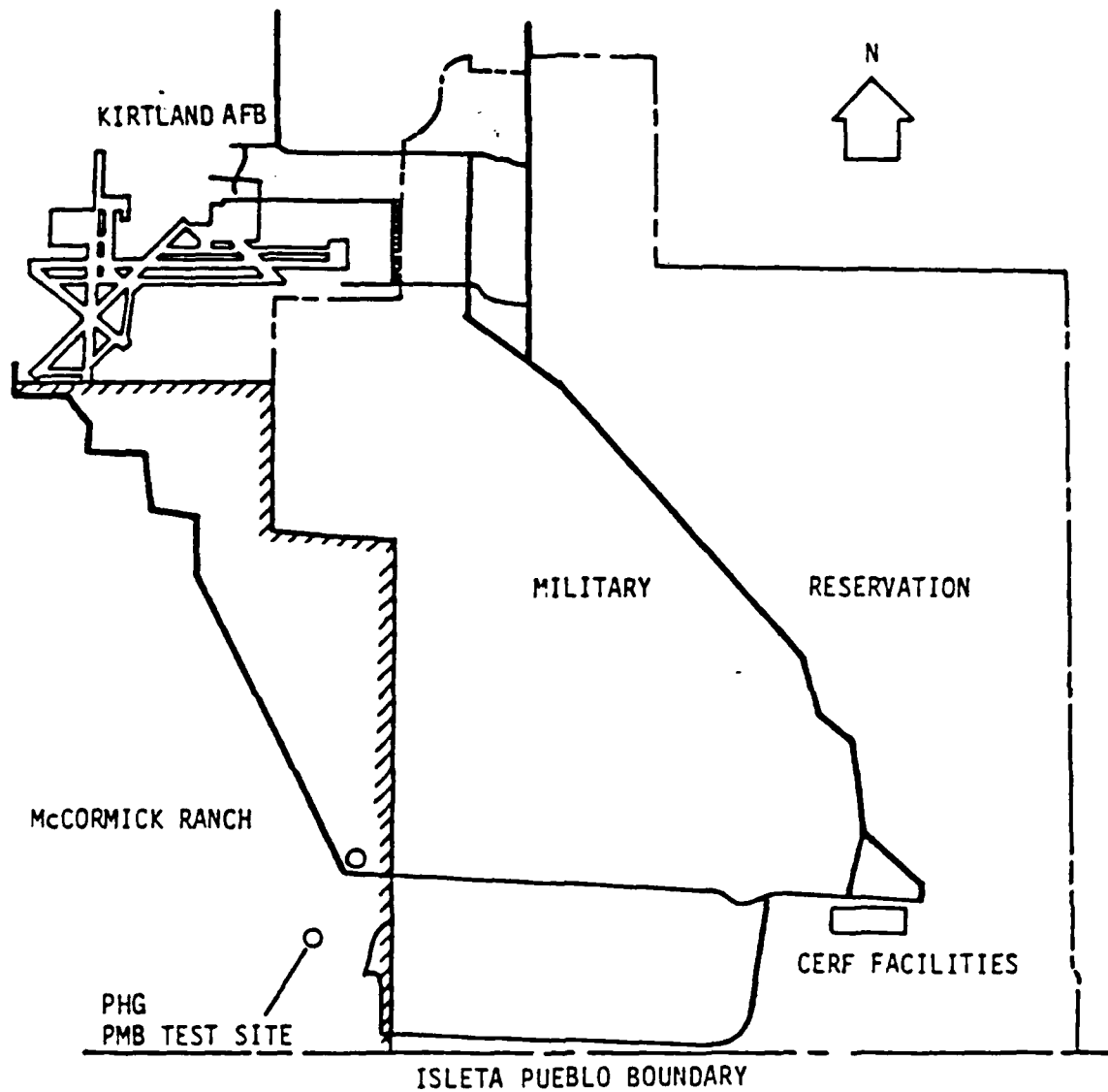
Figure 1. General map of the PMB and PHG test sites.

Data Analysis Technique

The moving window analysis technique can resolve broad frequency band recordings of multi-mode transient signals. Fourier spectral amplitudes as functions of period and group arrival time are interpreted in terms of Rayleigh-wave group velocity associated with each of the individual modes of propagation. The Rayleigh surface waves are analyzed for the fundamental and first-higher modes.

The analysis begins with the extraction of a section of a digitized seismogram f(t) using a rectangular time window w(t) centered at a time t_n which corresponds to a group velocity $U_n(T)$. The length of the extracted segment is variable, but is proportional to the produce of a fixed window factor W and the current wave period of analysis T_n. The representation is:

$$w(t) = 1 \qquad t_n - 1/2 \ WT < t < t_n + 1/2 \ WT_n$$

$$w(t) = 0 \qquad \text{otherwise}$$

$$\text{and } s(t) = f(t) \cdot w(t).$$

Experimental analyses have indicated that reliable results are obtained when the window length (W) is 4-6 times the period.

The next step in the moving window analysis is the multiplication of the windowed seismogram by a modulating symmetrical function q(t) centered at times corresponding to a particular group velocity in a series of equally spaced velocities.

The resulting time series is h(t) = g(t).s(t). Several types of modulating functions can be used, and a common function which has been applied is q(t) = cos2(πt/WT).

Multiplication of the specified time series by a window function is equivalent to convolution of the corresponding spectra in the frequency domain, and each spectral component of the time series will possess a shape resembling that of the Fourier transform of the applied window. The purpose of the modulation function is to give greater weight to that portion of the seismogram which corresponds to the group velocity of interest. Modulation also diminishes the side lobes in the frequency domain produced by analysis of a truncated signal. The final step of the moving window analysis involves taking the Fourier transform of the prepared signal h(t) to extract the spectral amplitudes and phases (Landisman and others, 1969).

The data are then displayed and contoured on a two-dimensional plot of the spectral amplitude values as a function of group velocity versus wave period. The dispersion curve is traced through the amplitude maxima for each period. The general result is illustrated in Figure 2 in the form of contour lines for selected amplitude values. The amplitude maxima which represent the group velocity data are indicated by dots. The contours represent amplitude values (zero to Z) that are normalized with respect to the maximum value at each period rather than absolute levels.

Results

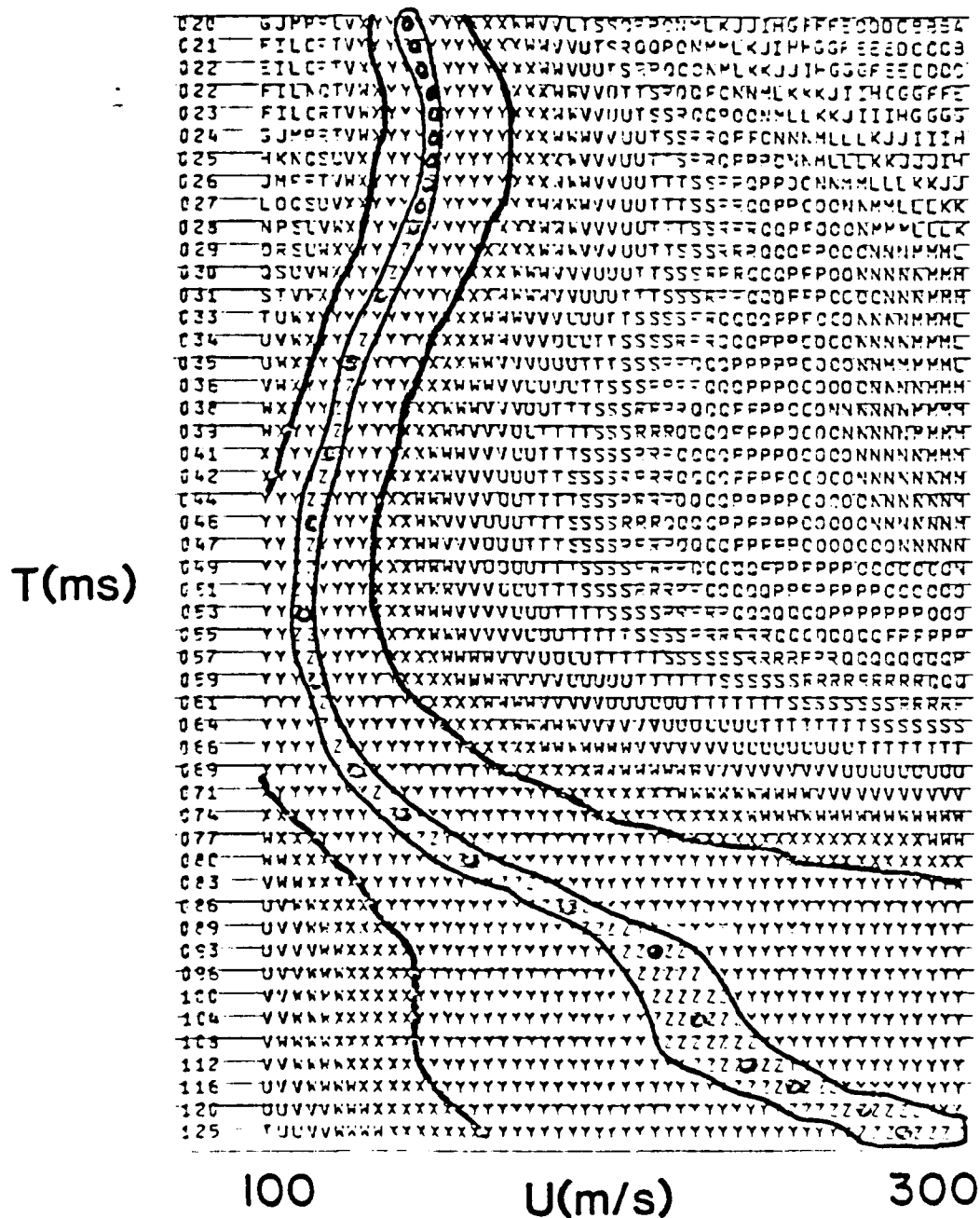The dispersion data for the PMB tests are presented for the

Figure 2. Example of output from moving window analysis, T = period in milliseconds (ms) and group velocity U (m/s).

ground motion observations at distance ranges of 73.2 m and 228.6 m. Representative time series for these distances are presented in Figures 3 and 4, respectively. The results from the moving window analysis are then presented in Figure 5 and 6, respectively. The group-velocity dispersion data are finally shown in Figure 7. The Rayleigh-wave dispersion curves indicate group velocities U=224-264 m/sec for period range T=50-164 msec. These data are interpreted as fundamental mode dispersion from the recordings at a distance of 228.6 m. The first higher-mode dispersion data were determined from recordings at a distance of 73.2 m. The associated group velocity range is 260-300 m/sec for periods of 25-59 msec. The various symbols represent different high-explosive tests for the same distance.

Ground motion records from the PHG test series are presented in Figures 8, 9, 10, and 11 representing distances of 10.9, 14.6, 18.4 and 35.8 m, respectively. The corresponding group-velocity dispersion data are shown in Figure 12. The pattern of dispersion for recordings at distances of 10.9 and 14.6 m is characterized by a monotonic decrease for velocity range 260 to 108 m/sec with period range T=20-100 msec. The time records exhibit the long period waveform usually identified as the "spall" wave associated with explosions. Stump (1981) has modeled these specific waveforms, and concluded that Rayleigh-waves can generate tensile stress components in the vertical direction which may produce the spall waveform. Consequently, the observed dispersion pattern probably represents the spall phase, but may also include dispersion from body waves at the short periods.
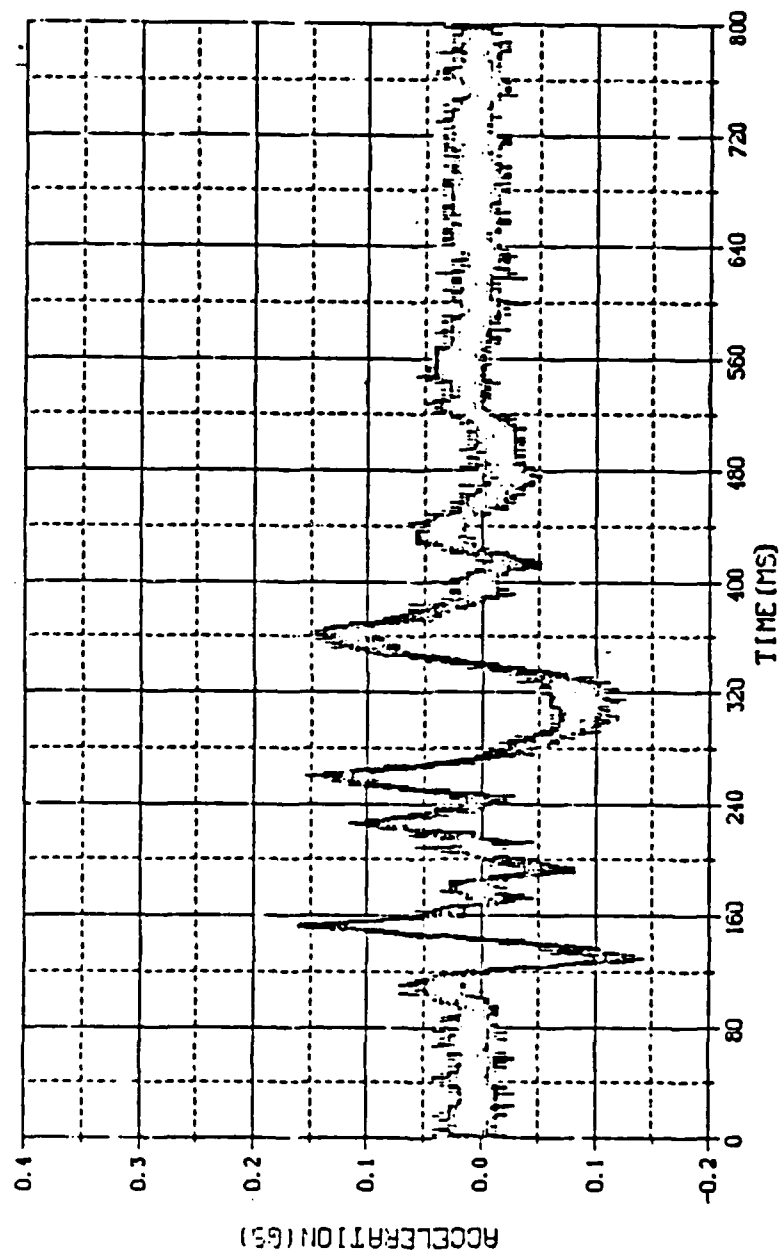
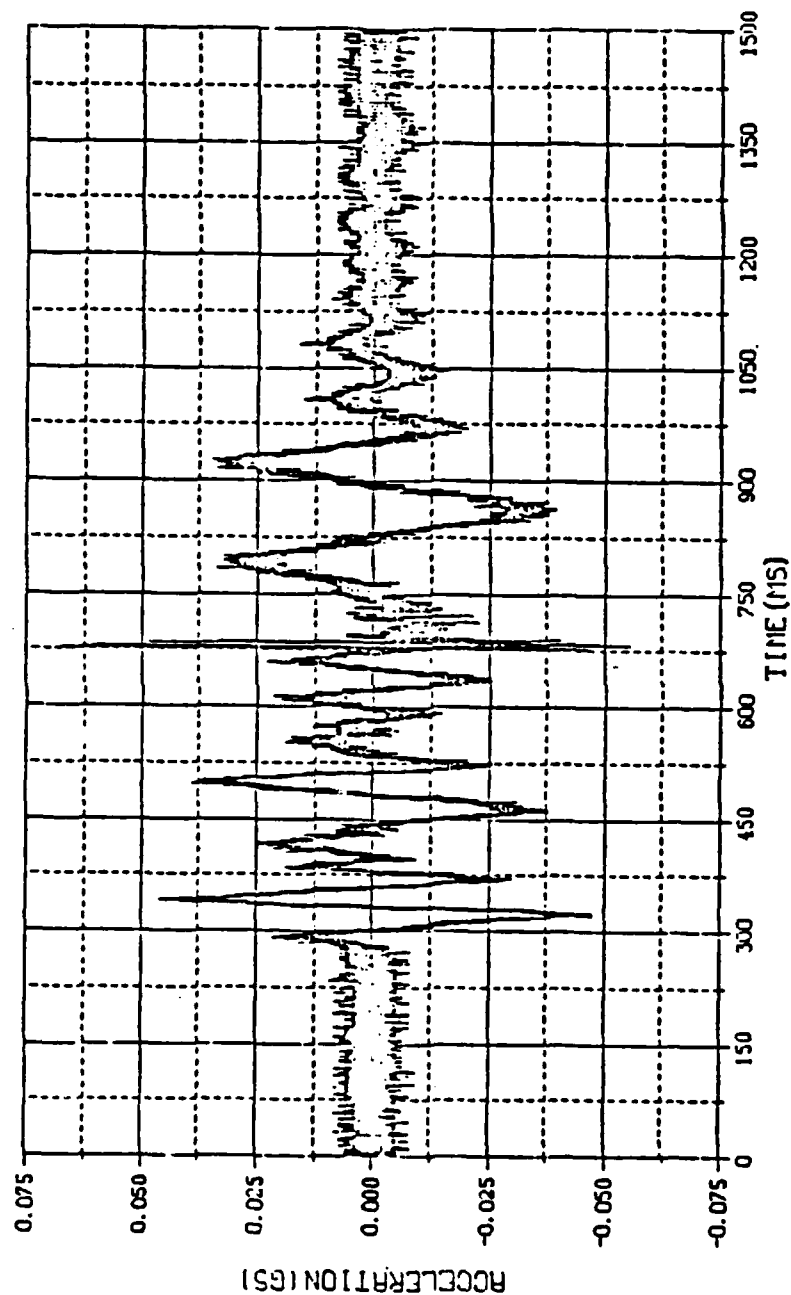Figure 3 PMB ground motion record at distance of 73.2 m.

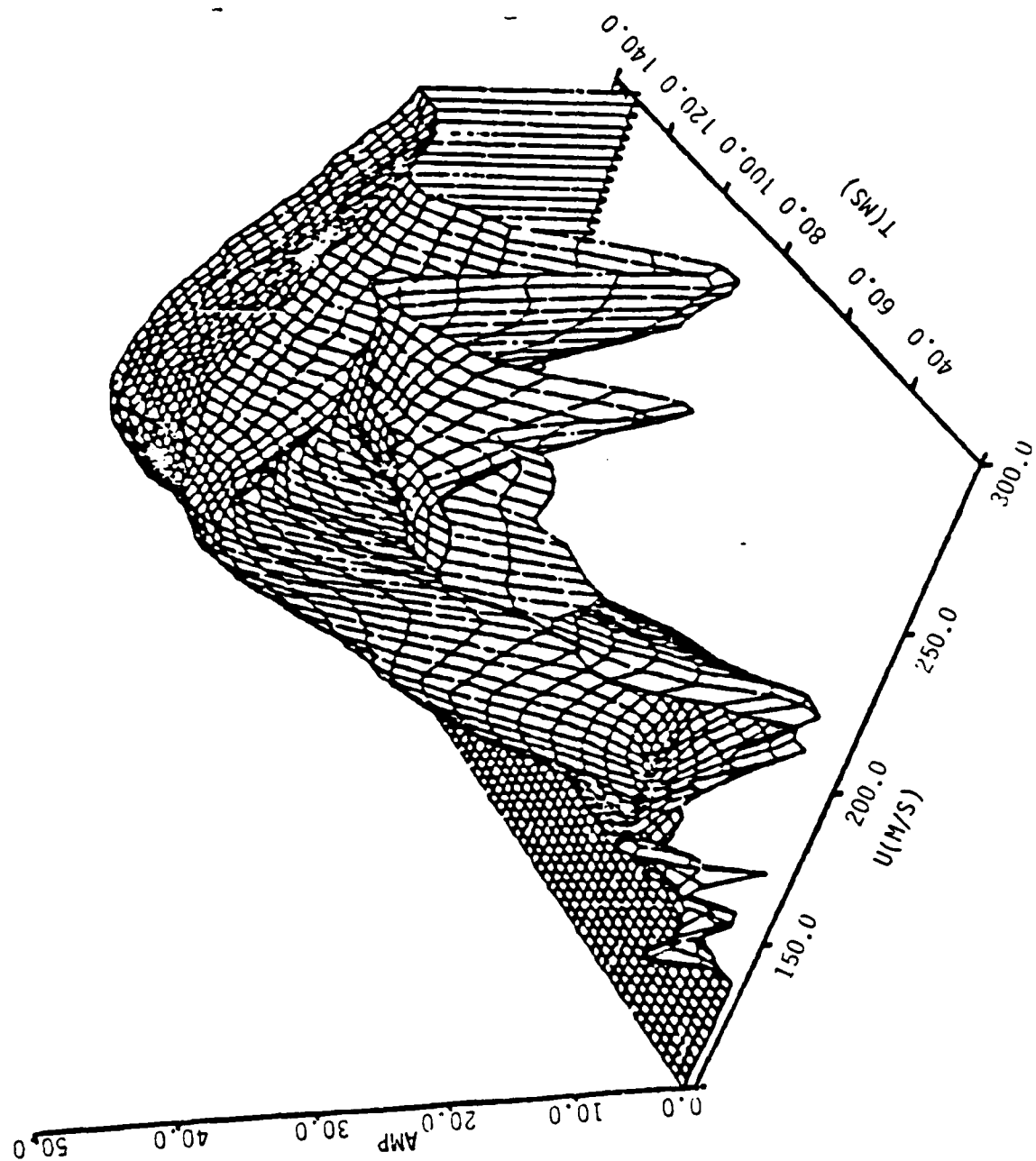Figure 4. PMB ground motion record at distance of 228.6 m.

Figure 5. Moving window technique results for PMB-06 recorded at a distance of 73.2 m.
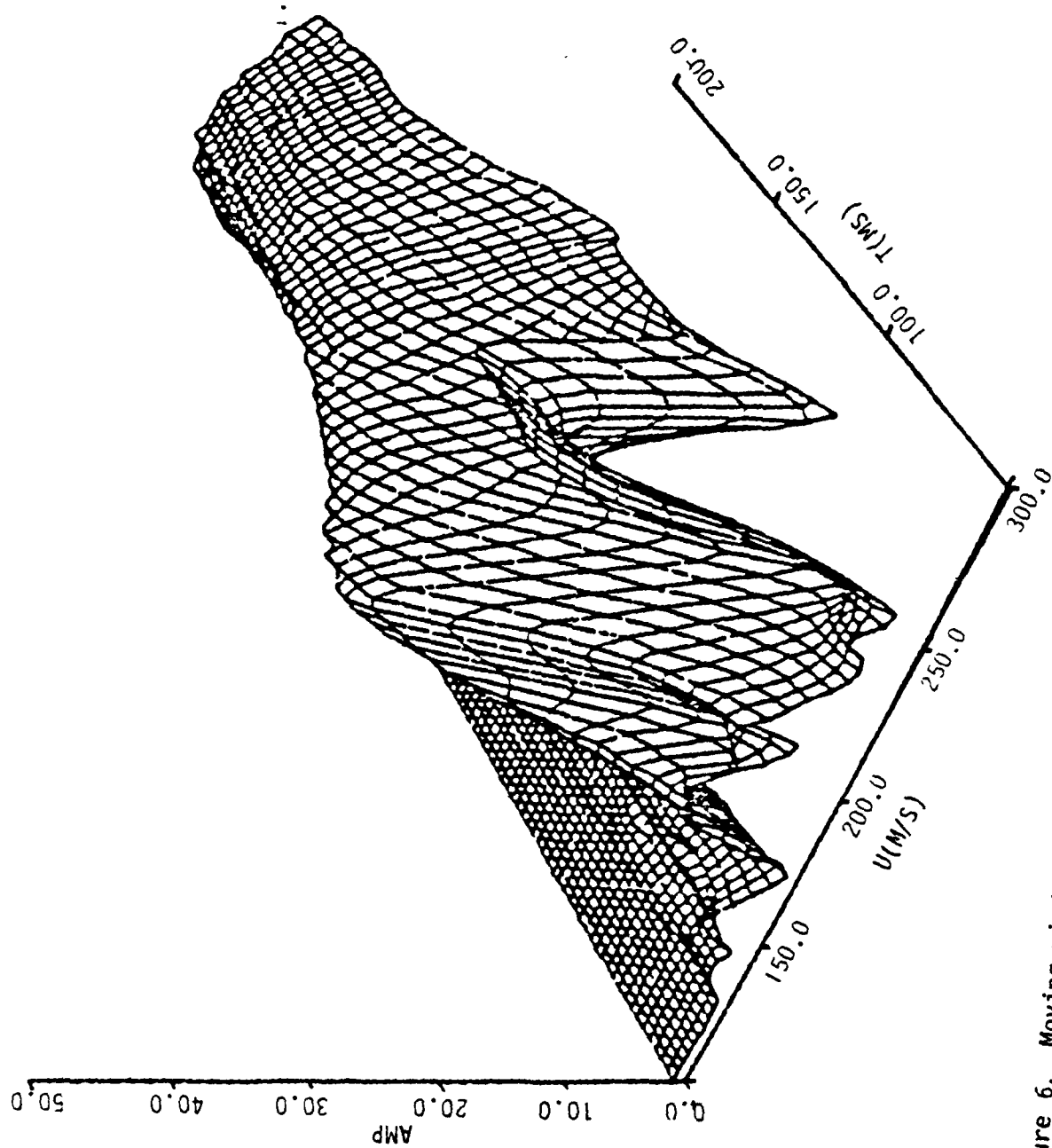
Figure 6. Moving window technique results for PMB-06 recorded at a distance of 228.6 m.
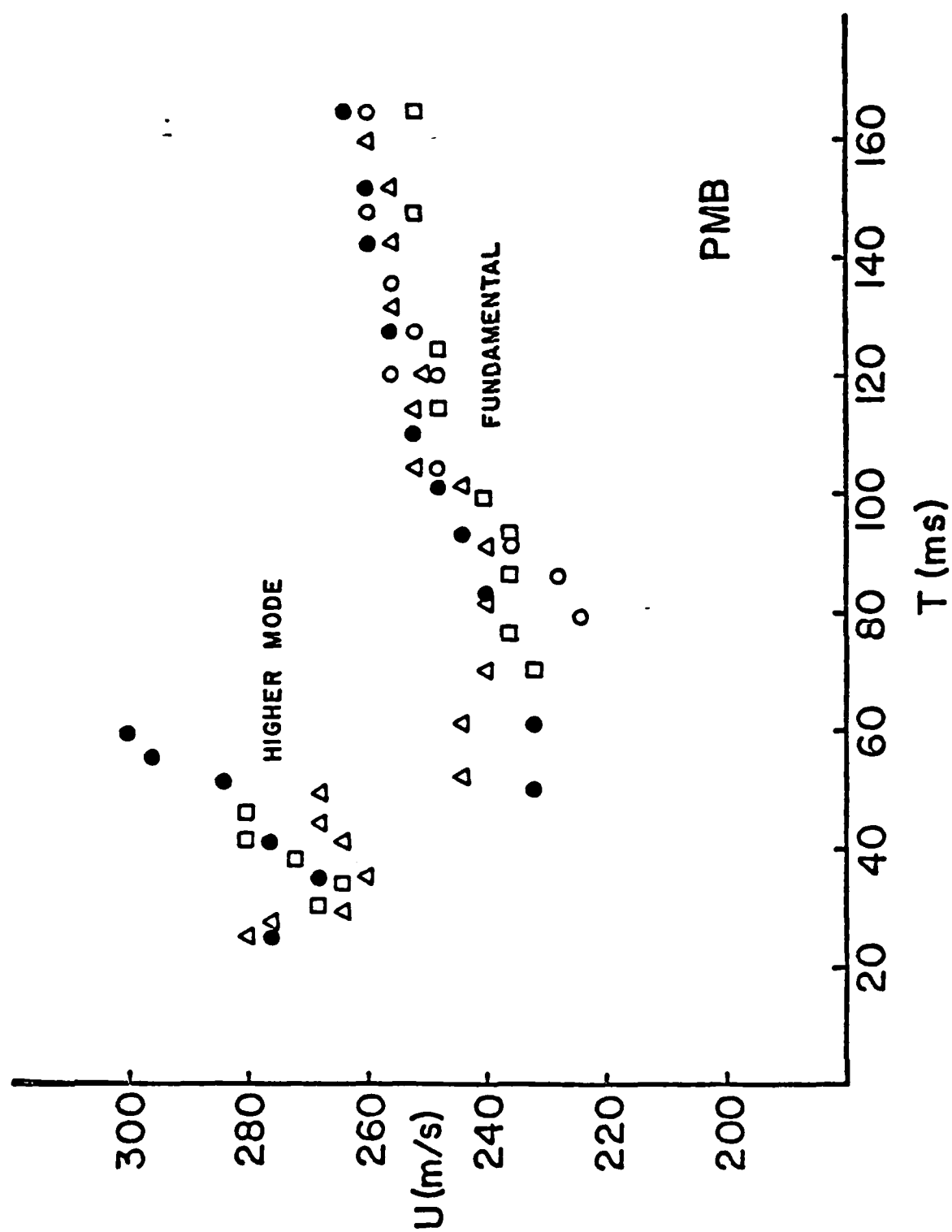
Figure 7 . Rayleigh wave, group-velocity dispersion for PMB data set.
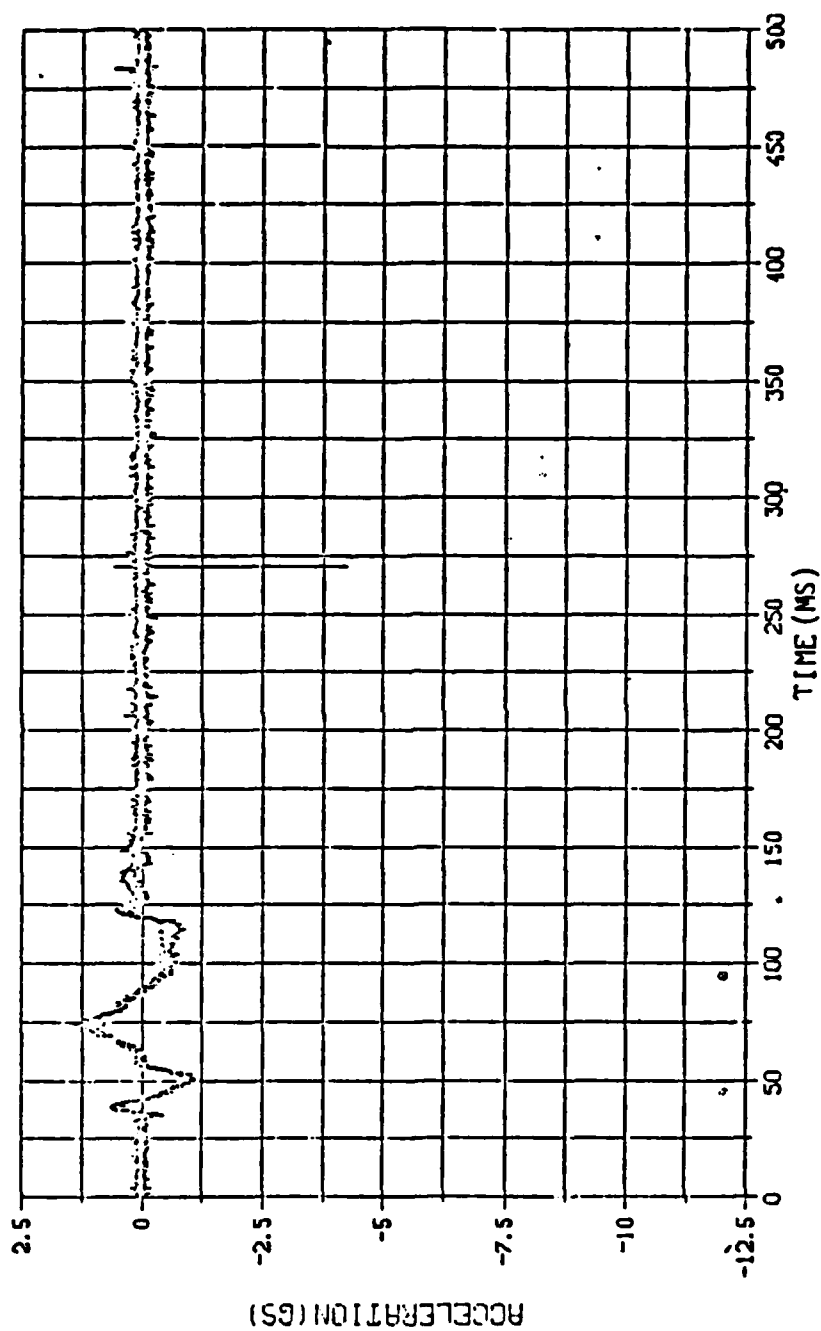
Figure 8. PHG ground motion recorded at a distance of 10.9 m.
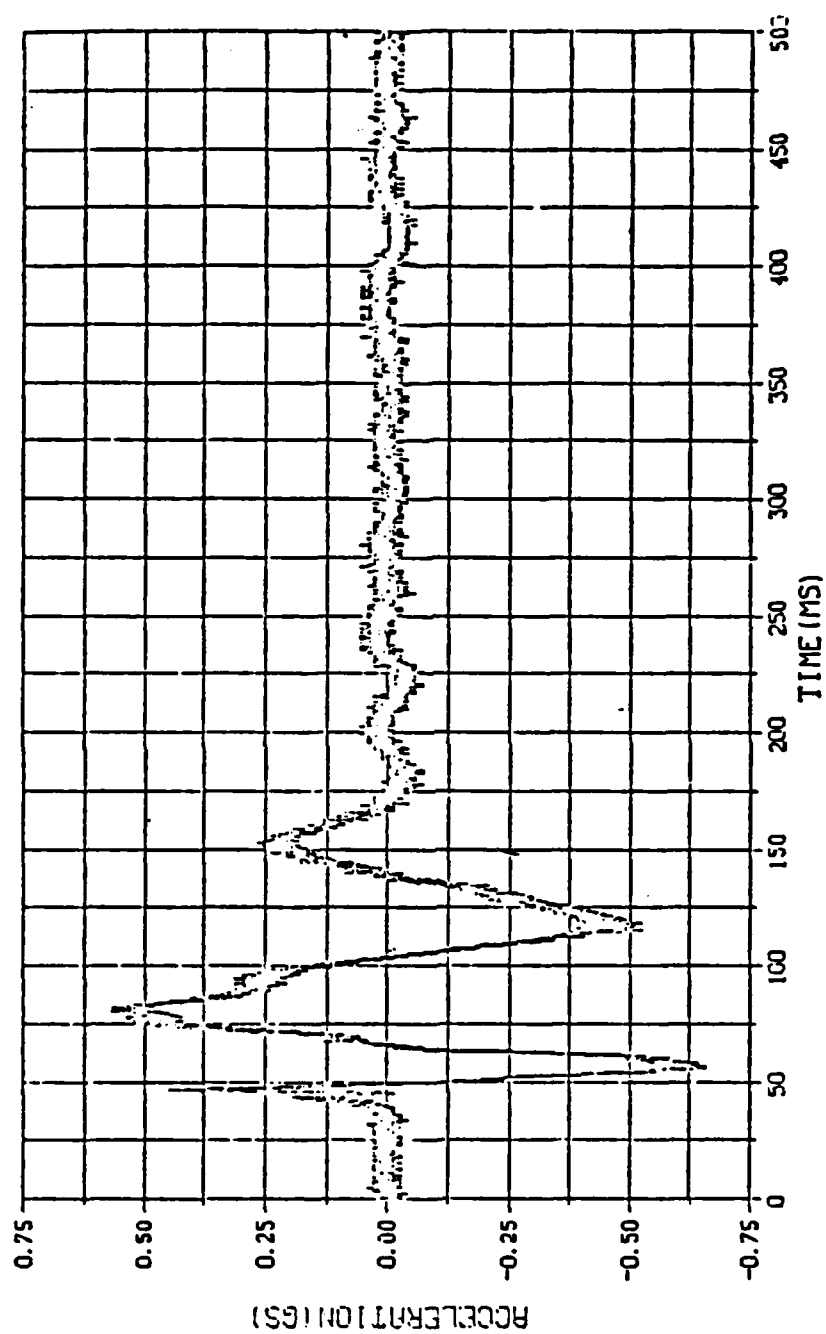
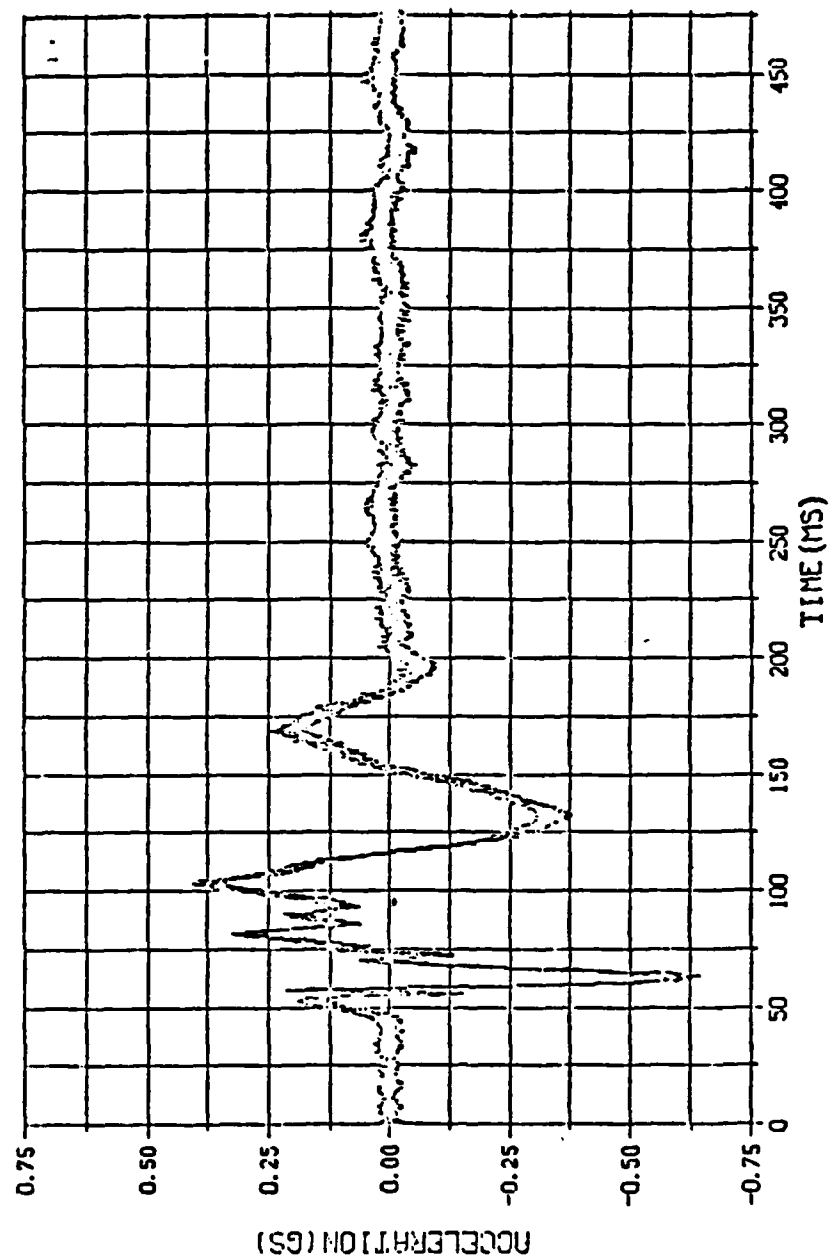Figure 9. PHG ground motion record at a distance of 14.6 m.

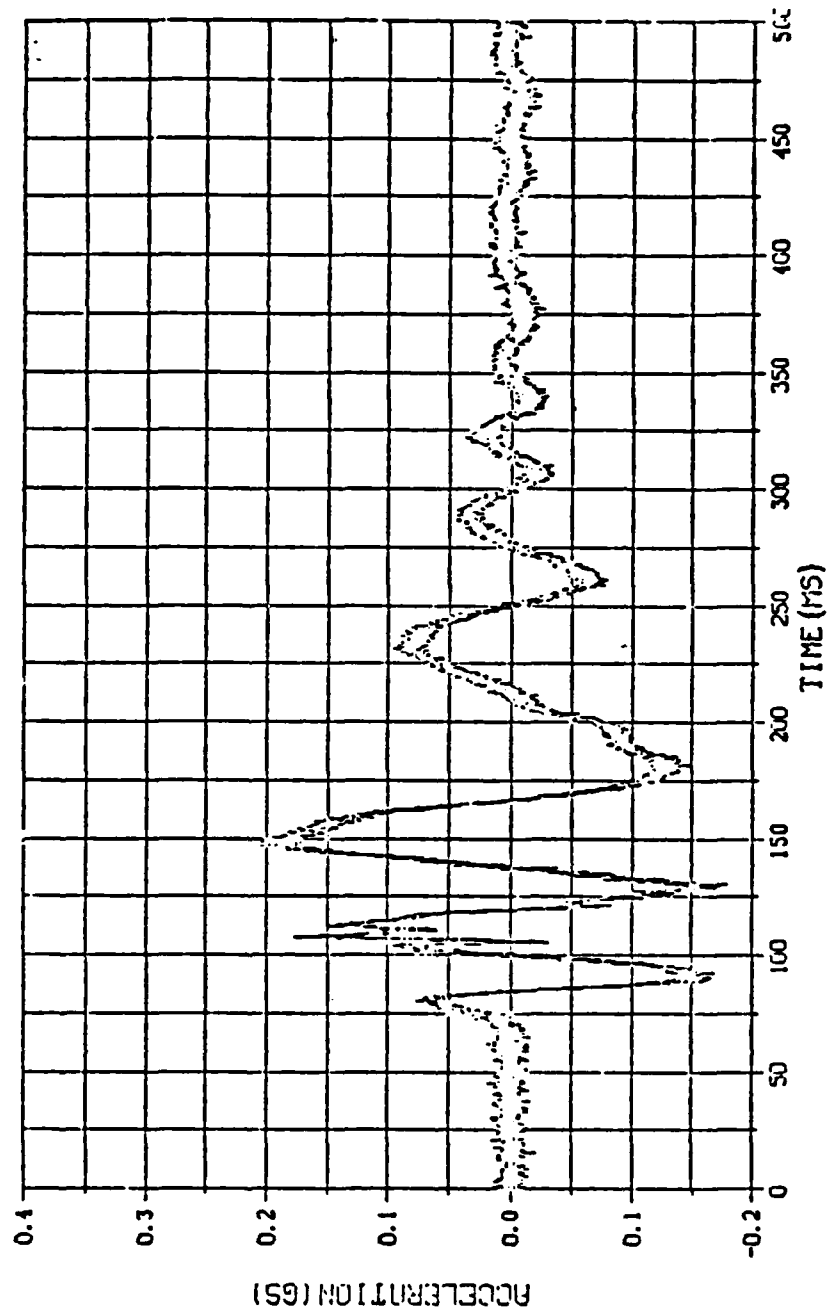Figure 10. PHG ground motion recorded at a distance of 18.4 m.

Figure 11. PHG ground motion recorded at a distance of 35.8 m.
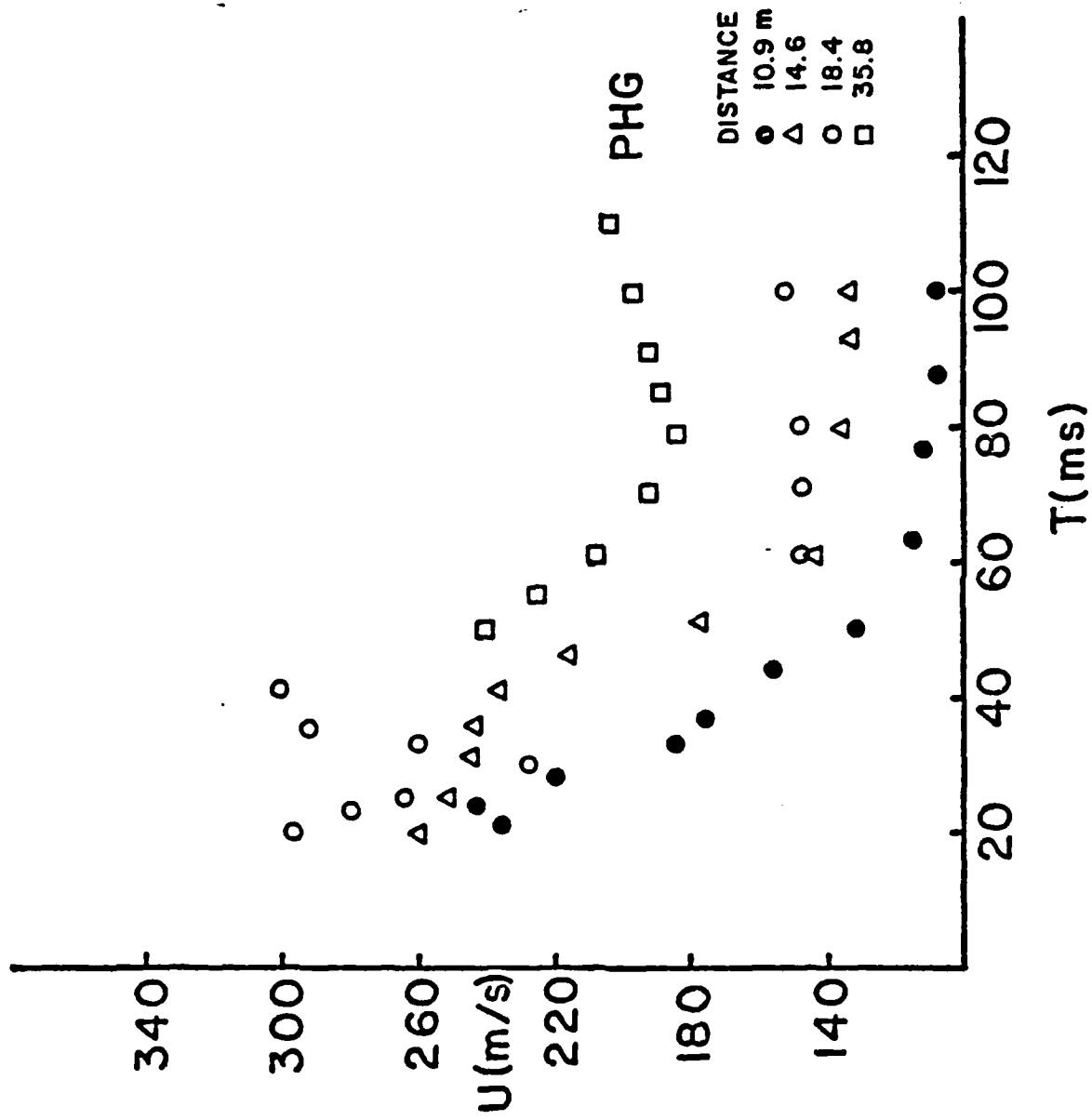
Figure 12. Rayleigh wave group-velocity dispersion for PHG data set.

The group-velocity data recorded at 18.4 m shows dispersion representing either a higher-mode Rayleigh-wave or possible body wave. The longer period dispersion may still represent the spall phase at this distance. At the distance of 35.8 m, the dispersion pattern is typical for a fundamental Rayleigh-wave mode. The associated group velocities are 240-200 m/sec with T=50-110msec. These velocities are approximately 20% slower at T=80 msec than those velocities observed from the PMB data even though the test site is the same.

Theoretical dispersion curves are generated to match the observed Rayleigh-wave group velocities by utilizing the Haskell method. The technique requires a model with parallel layers to simulate the near-surface geologic structure. The input elastic parameters are P- and S-wave velocities, density, and layer thickness. The Haskell method is used with a trial and error approach of selecting model parameters to generate dispersion curves which match the observed data. Consequently, several models will produce satisfactory data fits. Two crustal velocity models (Stump and Reinke, 1981) have been determined for the McCormick Ranch from previous geophysical studies. The model parameters are presented in Table 1.

The dispersion curves from the pmb data set and theoretical models are presented in Figure 13. The dispersion curves from the two models provide an approximate upper and lower bound for the observed data in the period range of 100-160 msec. Good agreement of the data sets occur for the periods T=70-90 msec. In general, at a depth of 0.4 λ_R (wavelength of the Rayleigh waves) the shear
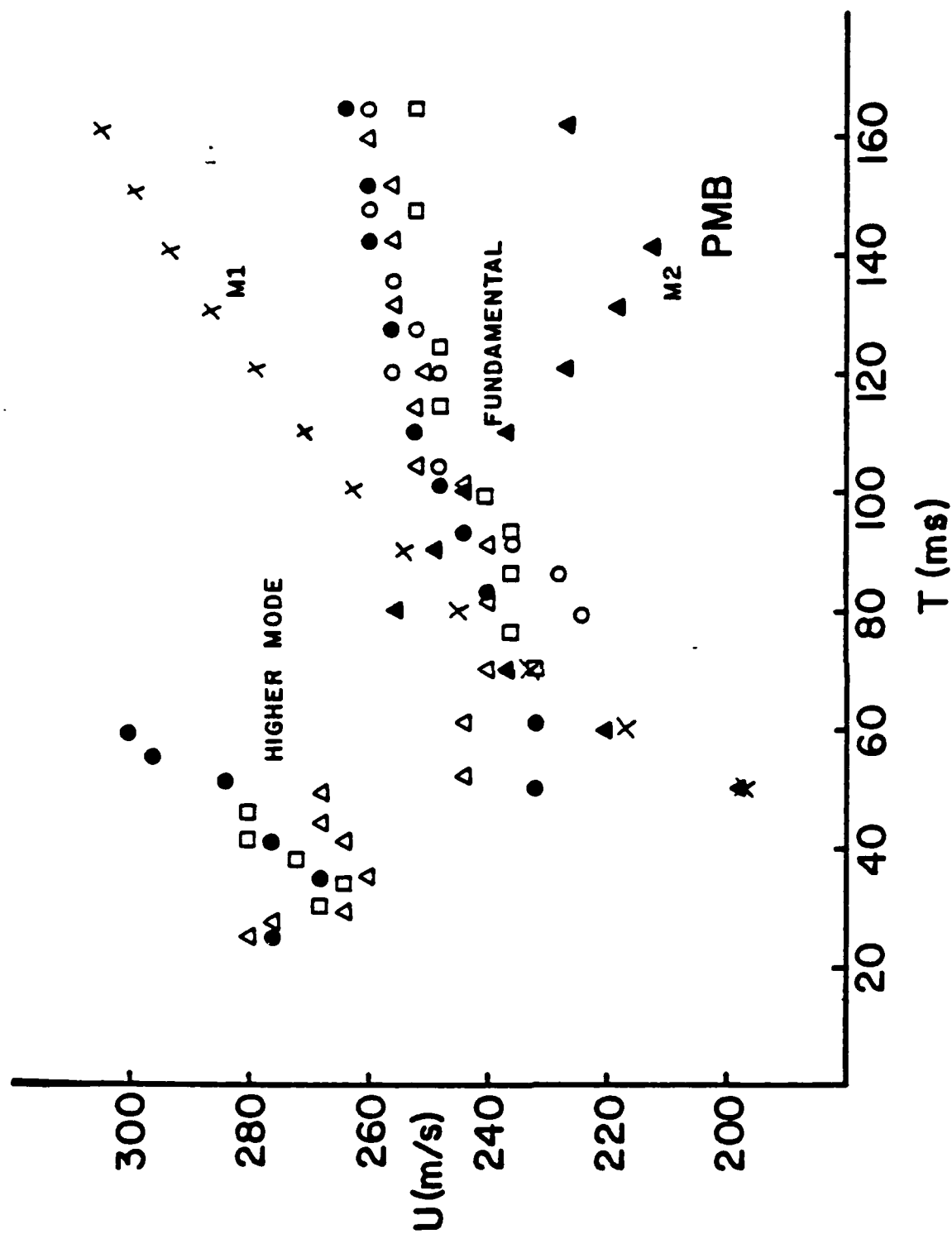
Figure 13. Dispersion curves for PMB data set and theoretical models M1 and M2.

TABLE 1.   VELOCITY MODEL PARAMETERS

Model	Vp(m/s)	Vs(m/s)	ρ(g/cc)	h(m)
M1	366	244	1.80	4
	671	366	1.90	10
	823	366	2.00	10
	1130	610	2.10	-
M2	366	244	1.80	4
	671	366	1.90	10
	823	400	1.90	-

wave velocity has the greatest effect on the value of the group velocity at the given period. For example, if the period is 160ms, the Rayleigh waves are influenced by a corresponding depth of about 22 m. Therefore, the group-velocity dispersion data are limited in the resolution of the model depth and associated shear wave velocity distribution.

Finally, the group velocity data are utilized in the inversion procedure for the shear velocity distribution. In addition, attenuation values of 50-100 are incorporated, but no inversion is performed. The layered mode M1 is used as the initial starting model. Since the layer thicknesses have been determined from refraction studies, no inversion on this parameter is attempted. The observations of possible higher-mode group velocities are also used to constrain the final velocity model.

The resulting group velocity model from the inversion procedure

is presented in Figure 14. An average fit of the observed data is obtained for the period range T = 60-100 ms. The variation in the observed group velocities is presumably due to the various near surface soils which have been sampled by the varying station azimuths. The results from T=100-150 ms show a better fit which also coincides with less scatter in the observed data. The shear wave velocity model derived from the inversion process is presented in Figure 15. Although this model is nonunique, the velocity profile is consistent with the refraction survey and associated Rayleigh wave dispersion.

Conclusions

In conclusion, Rayleigh-wave group-velocity dispersion has been determined from high-explosive ground-motion records using the moving window technique. The fundamental mode dispersion was 225 to 264 m/s for the period range 50-165 ms. In addition, higher mode dispersion was observed for the period range 25-60 ms with group velocities equal 280-305 m/s. Also, possible dispersion was observed from the spall phase. The observed dispersion was inverted to yield a shear-wave velocity model of 245-610 m/s to a depth of 24 m at the McCormick Ranch test site.
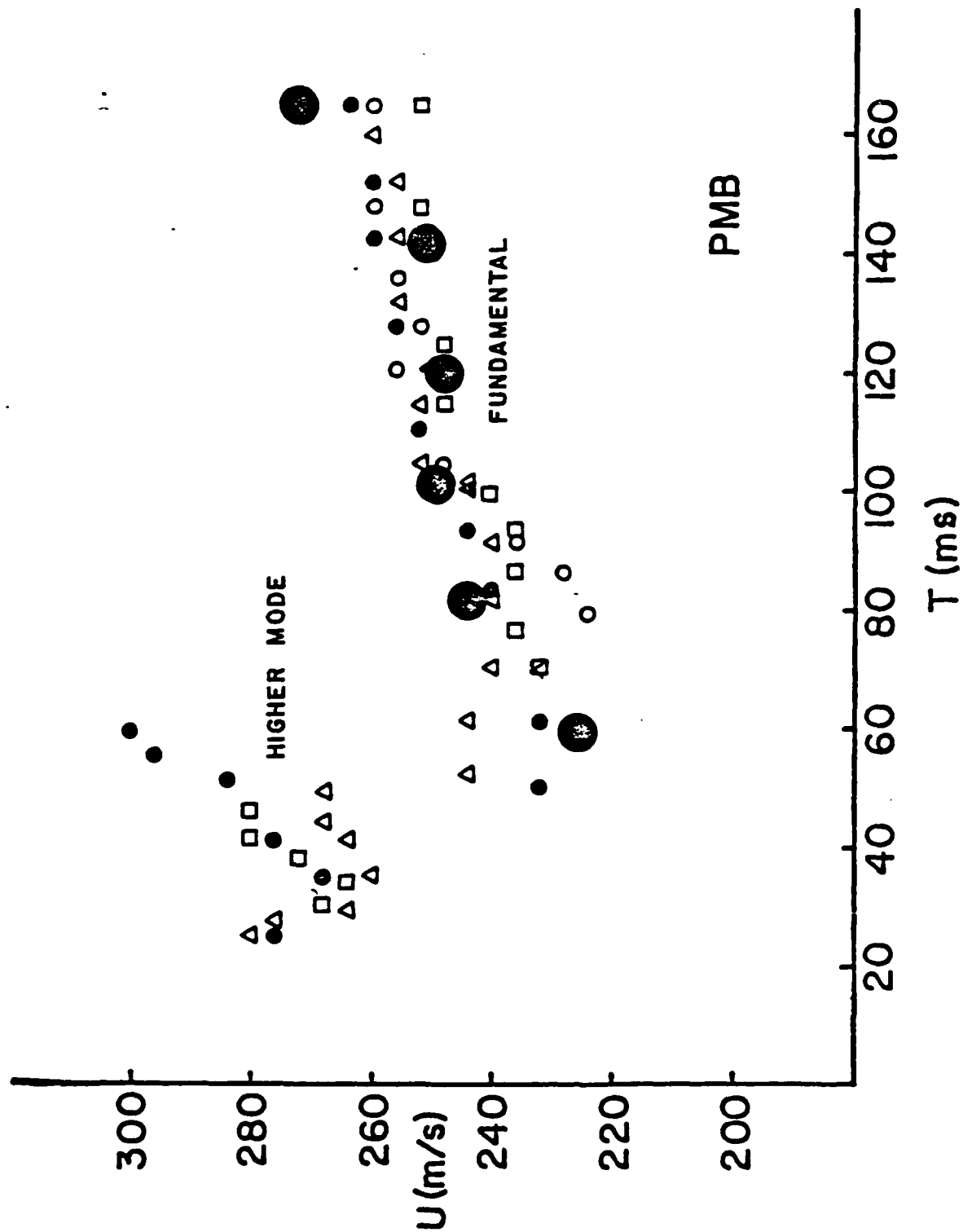
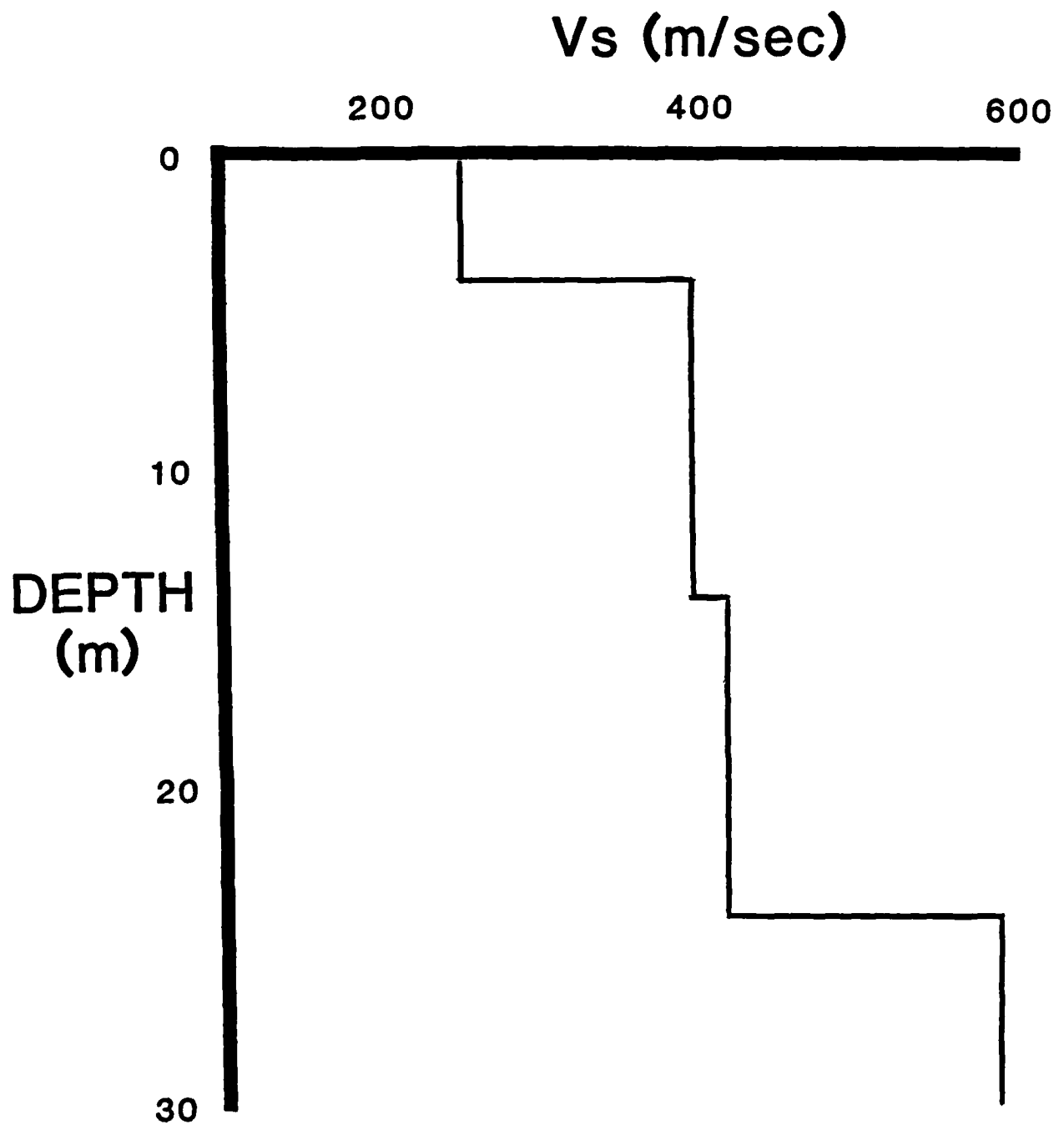Figure 14. Group velocity model (large dots) determined from inversion process.

Figure 15. Shear wave velocity model from inversion process.

ACKNOWLEDGEMENTS

REFERENCES

Babcock, S. (1980). Prehybrid Gust Phase II Quick Look Report CERF-AG-27, Engineering Research Institute, Univ. of New Mexico.

Barker, T.G. and J.L. Stevens. (1983). Shallow Shear Wave Velocity and Q Structures at the El Centro Strong Motion Accelerograph Array, Geophys. Res. Letters, v. 10, p. 853-856.

Brown, R. W. (1980). Pre-Multiple Burst (PMB II-78) Data Report, AFWL-TR-79-206, Air Force Weapons Lab, Kirtland AFB.

Cherry, J. T., S.M. Day, N. Rimer, W. L. Rodi, and H. J. Swanger (1978). Rayleigh Waves in MX Valleys, Science Systems and Software, Technical Report 11084.8-009.

Haskell, N. A. (1953). The Dispersion of Surface Waves on Multilayered Media, Bull. Seis. Soc. Amer., v. 43, pp. 17-34.

Kovach, R. L. (1978). Seismic Surface Waves and Crustal and Upper Mantle Structure, Reviews of Geophysics and Space Physics, v. 16, pp. 1-13.

Lancsoz, C. (1961). Linear Differential Operators, D. Van Nostrand, London.

Landisman, M., A. Dziewonski, and Y. Sato (1969). Recent Improvements in the Analysis of Surface Wave Observations, Geophys. J. R. astr. Soc., v. 17, pp. 369-403.

Rodi, W. L., P. Glover, T. Li, and S. S. Alexander (1975). A Fast Accurate Method for Computing Group Velocity Partial Derivatives for Rayleigh and Love Modes, Bull. Seism. Soc. Am., v. 65, p. 1105-1114.

Silva, W. (1978). Wave Propagation in Anelastic Media With Applications to Seismology, PH.D. Thesis, U.C. Berkeley.

Simila, G. W. (1980). Seismic Velocity Structure and Associated Tectonics of Northern California, Ph.D. Thesis, U.C. Berkeley.

_____(1982). Shear-wave Velocity Rayleigh-Wave Group Velocity Dispersion Analysis, U.S. Air Force Weapons Lab, Kirtland AFB, AFWL-TR-82-08, 33 p.

Stump, B. W. (1981). Source Characterization of Bermed Surface Bursts, Technical Report, Air Force Weapons Lab, Kirtland AFB.

Stump, B. W. and R. E. Reinke (1981). Geophysical Studies at McCormick Ranch, New Mexico and the Importance of Spall Waveforms in High-Explosive Testing, Technical Report, Air Force Weapons Lab, Kirtland AFB.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited	
2b. DECLASSIFICATION DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR·TR· 8 ? · 0 2 7 8	
6a. NAME OF PERFORMING ORGANIZATION California State University, Northridge	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U.S. Air Force Office of Scientific Research	
6c. ADDRESS (City, State and ZIP Code) 18111 Nordhoff St. Northridge, CA 91330		7b. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB, D. C. 20332-6448	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAFOSR	8b. OFFICE SYMBOL (If applicable) NP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-82-0138	
8c. ADDRESS (City, State and ZIP Code) Buidling 410 Bolling AFB DC 20332-6448		10. SOURCE OF FUNDING NOS.	

	10. SOURCE OF FUNDING NOS.		
PROGRAM ELEMENT NO	PROJECT NO	TASK NO.	WORK UNIT NO
61102F	2309	D9	N/A

11. TITLE (Include Security Classification) Inversion of Rayleigh Wave Group Velocities from High-Explosive Tests

12. PERSONAL AUTHOR(S) Simila, Gerald Wayne

13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 1 Apr 82 TO 31 Mar 83	14. DATE OF REPORT (Yr., Mo., Day) January, 1985	15. PAGE COUNT 29

16. SUPPLEMENTARY NOTATION

17	COSATI CODES		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Rayleigh wave, group velocity, high explosive tests
FIELD	GROUP	SUB GR	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☒ DTIC USERS ☐		21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr Henry R. Radoski		22b TELEPHONE NUMBER (Include Area Code) 202/767-4907	22c. OFFICE SYMBOL NP

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE   UNCLASSIFIED

END

FILMED

4-85

DTIC